Duct system performance and energy losses in large commercial buildings

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Abstract

This paper presents the findings of recent work characterizing thermal distribution systems in four large commercial buildings by the Lawrence Berkeley National Laboratory (LBNL). The buildings are multi-story large-office buildings or retails buildings with floor spaces of more than 2,000 m^2. They typically contain single-duct or dual-duct constant air volume (CAV) systems, or variable air volume (VAV) systems. Thermal distribution losses in the duct systems studied are categorized into air leakage and conduction, with the latter including convective and radiative losses. This paper reports air leakage results in terms of effective leakage area (ELA) and ASHRAE-defined duct leakage class, and compares with those found in previous studies. The new data of leakage classes indicate that air leakage in large commercial duct systems varies significantly from system to system, and from system section to system section. Most of the duct systems measured are much leakier than the ductwork specified as "unsealed ducts" by ASHRAE. Energy losses due to air leakage and heat conduction through duct systems are significant.

1 Introduction

Commercial buildings with floor areas over 2,000 m^2, account for about 10% of commercial buildings in the U.S. and California, corresponding to more than 60% of the building floor area (EIA 1991). Previous characterizations of air leakage from ducts in light commercial buildings found that leakage airflow from ducts in light commercial buildings equals approximately one quarter of system fan flow (Levinson et al. 1997, Delp et al. 1998a). A field study (Fisk et al. 1999) reports that duct system leakage classes range from 60 to 270 in large commercial buildings. These values are generally well above the ASHRAE value of 48 assigned to "unsealed" rectangular metal-ducts (ASHRAE 1997). However, the ASHRAE values, specified for different duct types instead of duct systems, neglect leakage at connections of ducts to grilles, diffusers, registers, duct-mounted equipment, or access doors. These indicate that air leakage induces significant thermal energy losses during the transportation of conditioned air through duct systems. The characterization efforts by the Lawrence Berkeley National Laboratory (LBNL) also uncovered significant thermal losses due to heat conduction through duct walls (Fisk et al . 1999). Underestimation of air leakage and heat conduction may lead to inappropriate HVAC system sizing and design, e.g., excessive fan-power requirement, which results in inefficient operation of HVAC equipment.

Compared to light commercial buildings, a much larger fraction of HVAC energy use in large commercial buildings is associated with fan energy use, which is dramatically, impacted by air leakage and conduction losses (Modera et al. 1999). Based upon simulation of a variable air volume (VAV) system with a leakage class of 137, Franconi et al. (1999) report an HVAC energy cost increase of 14% and an annual fan energy use increase of 55%. This suggests that sealing duct leaks in large commercial buildings may be an effective measure to increase energy efficiency in this sector. Other benefits to airtight duct systems in such buildings include better control of airflow at the registers (flow balancing) and potentially better indoor air quality and thermal comfort. There is, however, a lack of information about the performance of thermal distribution systems, especially in large commercial buildings. To further understand the existing thermal distribution systems in real buildings, it is necessary to characterize the air leakage through ducts and the thermal performance of system operation in more buildings.

2 Objectives

The overall goal is to provide new data that will allow the construction and energy services industries to reduce the energy waste associated with thermal distribution systems in large commercial buildings. The study aims at advancing the state of knowledge about thermal distribution system performance and energy losses in large commercial buildings, and identifying improvement opportunities of reducing thermal losses. The specific objectives are 1) to assess air leakage through ducts, measuring both duct system leakage area and pressure, and the difference between the upstream and downstream airflow rates; and 2) to assess the magnitude of conduction heat gains and/or heat losses in duct systems.

3 Approaches

The main approach is to obtain field data on the thermal performance of duct systems in large California commercial buildings, including characterizations of the spaces in which those ducts are located (Xu et al. 1999). The thermal performance evaluation consisted of both air leakage and heat conduction measurements. The study measured air leakage through ducts of five large systems in four large commercial buildings. Since the buildings in this study were generally occupied, the tests had to be as non-obtrusive as possible. This required working outside of the normal (daytime) schedules of the occupants. Studies on each of the systems included contacts with building managers and engineers; system characterization by walk-throughs and literature review; measurements of air leakage, pressure, airflow, and heat gain or loss; and data analyses. The following describes the measurements used in this study.

3.1 Duct leakage area measurements

To characterize the airtightness of thermal distribution systems, the effective leakage areas (ELAs) of isolated sections of ductwork were measured using fan-pressurization procedures. The ELA is defined as the area of a perfect nozzle that, at some reference pressure difference, would produce the same flow as that passing through all the leaks in the system. By artificially creating a series of pressure differences across the leaks, the ELA can be determined by fitting the flow and pressure data to Eq. (1):

$$Q = \frac{ELA}{10^4}\sqrt{\frac{2\,\Delta P_{\mathrm{ref}}}{\rho}}\left(\frac{\Delta P}{\Delta P_{\mathrm{ref}}}\right)^n , \tag{1}$$

where Q is the volumetric flow rate (m^3 s^{-1}), ELA is the effective leakage area (cm^2), ΔP is the pressure difference across the leaks in the system (Pa), ΔP_{ref} is a reference pressure difference (Pa), n is the flow exponent (-), and ρ is the air density (kg m^{-3}).
The method is well documented in the literature (SMACNA 1985; ASTM 1987, Delp et al. 1997). ELA is estimated to be about ± 10%. The reference pressure ΔP is usually set to 25

Pa for characterization of U.S. duct systems. To allow comparisons between different building systems, duct system ELAs were normalized either by the floor area served by the duct system or by the surface area of the ductwork.

The leakage class, C_L, is another common metric used to characterize the leakage area of U.S. duct systems. Using their leakage classes can compare the degrees of air leakage in duct systems of different sizes. ASHRAE (1997, Chapter 32) lists attainable leakage classes ranging from 3 to 12 for "quality construction and sealing practices," but notes that these attainable leakage classes do not account for leakage at connections to grills or diffusers, access doors, and other duct-mounted equipment. For unsealed ducts, ASHRAE predicts leakage classes of 30 to 48.

3.2 Air leakage ratio through ducts

Air leakage ratio, defined as the air leakage flow rate divided by the total airflow rate through a cross section in upstream of the ductwork, is used to characterize the degrees of air leakage from duct systems. To estimate the air leakage ratio through ducts, we measured the total airflow rate through a cross section in upstream of the ductwork using the tracer gas method, and measured the air leakage flow rate using two methods described as follows. Measuring air leakage flow rate remains a challenging task despite the considerable efforts undertaken in this area (Walker et al. 1998; Fisk et al. 1999). The two methods used to estimate the air leakage flow rates through duct systems are: a) estimate air leakage flow rates from ELAs and operating pressures based upon Eq. (1), and b) estimate air leakage flow rates by taking the difference between upstream airflow rate and sum of register flow rates. To measure airflow rates through supply registers, we used an LBNL-designed, fan-powered flow hood. The measurement results are more accurate than those using commercially available passive flow hoods are. The details of the apparatus were discussed in recent LBNL studies (Fisk et al. 1999; Xu et al. 1999) and will not be presented here.

3.3 Thermal loss through conduction

Thermal losses are due not only to air leakage but also to heat conduction. Conduction loss assessment focused on the measurement of temperatures in the system and on estimate of thermal loss. Thermal measurements were made with stand-alone temperature loggers in the plenum (downstream of the cooling/heating coil), in selected supply registers, in the room, in the ceiling cavity, and in the outside air. The battery-powered temperature loggers with external temperature sensors were Pro HOBOs (On-Set Computer Corporation, Pocasset, MA) with 0.03 °C resolution and an accuracy of ±0.2 °C in high-resolution mode. The temperatures measured by multiple collocated Pro HOBOs shows a maximum span of 0.25 °C and a standard deviation of less than 0.1 °C. Studies (Delp et al. 1998a, 1998b) evaluate the energy delivery effectiveness of heat transport through ducts in terms of the duct's "cumulative effectiveness," defined as the ratio of the energy delivered at the register to the potential available at the plenum (upstream of conduction losses). Since latent heat due to moisture contents could be negligible (e.g., in supply duct latent heat is zero during operation because the duct is normally pressurized), it equals the ratio of the sensible heat capacity forheating or cooling delivered at the register to the capacity available at the plenum. Based on the assumptions that the airflow through the ductwork is constant over time and space, and impact of leakage flow on temperature change is negligible, it can be simplified by calculating the temperature differential between the register temperature, plenum temperature and the reference temperature which is essentially the conditioned-space temperature.

For VAV systems, the airflow rates usually change over the course of a day. Although the assessment on energy delivery effectiveness has to be linked to the airflow rates over a period of time (e.g., a day), it makes sense to look at the "temperature effectiveness" for a shorter period of time during which the airflow can be considered constant. Borrowing from the cumulative effectiveness, we define the cumulative temperature effectiveness for a certain supply as the ratio of the temperature difference between the register and space to the temperature difference between the supply plenum and space for a certain period of time. Eq. (2) defines the *cumulative temperature effectiveness* $\tau_{s,i}(t')$ for heating or cooling delivery, an indicator for temperature gain/loss induced by heat conduction through system ducts:

$$\tau_{s,i}(t') \equiv \frac{\int_0^{t'} \left[T_{\text{terminal unit},i}(t) - T_{\text{room}}(t) \right] dt}{\int_0^{t'} \left[T_{\text{plenum}}(t) - T_{\text{room}}(t) \right] dt}, \qquad (2)$$

where t' is the elapsed period of time of interest, normally a combination of temperature swings; $T_{\text{terminal unit, i}}$ (t) is the temperatures of supply terminal unit i at time t (°C); $T_{\text{room}}(t)$ is the room temperature at time t (°C); $T_{\text{plenum}}(t)$ is the supply plenum temperature at time t (°C). Under stable airflow conditions, cumulative temperature effectiveness is equivalent to the ratio of the sensible heat capacity (energy) for heating or cooling delivered at the supply terminal unit to the capacity available at the plenum over a cumulative period of time, which equals the "cumulative effectiveness" used in previous studies (Delp et al. 1998). However, in general, the *temperature effectiveness* does not directly indicate energy delivery efficiency for VAV systems with or without induction units.

4 Results

We conducted field characterization testing on five HVAC systems (or system sections) in four large commercial buildings in northern California. Field study results include the physical characteristics of buildings and building systems, air leakage assessments using effective leakage areas (ELAs), air leakage classes, static pressures, and air leakage ratios, and evaluation of thermal losses due to heat conduction.

4.1 Effective leakage areas, air leakage classes, static pressures, and air leakage ratios

ELAs and static pressures were measured for five systems or their sections in four large commercial buildings. The system sections were selected for the VAV systems or dual-duct systems on the basis of physical accessibility. System L1 is in a supermarket building in which the supply and return ducts were tested separately. System L2 is a single-duct perimeter system in an office building. System L3 contains section L3a, the main duct upstream of the VAV boxes and induction units in the office building, and section L3b, one of the branches downstream of a VAV box with an induction unit. Section L4a and L4b in System L4 are two branches downstream of their VAV boxes with induction units in an office building. Sections a-d of System L5 are four branches downstream of their mixing boxes in an dual-duct system of another office building. The measured effective leakage areas, air leakage classes, and static pressures in large commercial building systems are summarized in Table 1.

Table 1. Measured air duct system effective leakage areas, air leakage classes, and static pressures in large commercial buildings

	System L1		System L2		System L3a	System L3b	System L4a	System L4b	System L5a	System L5b	System L5c	System L5d
Duct system description	CAV		CAV		VAV	VAV	VAV	VAV	Dual	Dual	Dual	Dual
	Supply	Return	Overall	Supply duct	Main Trunk	Branch	Branch	Branch	Duct	Duct	Duct	Duct
Year built	1996		1979		1979	1979	1980	1980	1990	1990	1990	1990
ELA per unit served floor area (cm2/m2 at 25 Pa)	0.3	0.3	0.3	0.1	0.1	0.7	0.3	0.3	5.1	2.0	7.7	5.0
ELA per unit duct surface area (cm2/m2 at 25 Pa)	2.5	8.8	1.9	0.7	0.7	5.4	0.9	1.3	9.9	12.9	11.5	9.7
Flow exponent (-)	0.59	0.52	0.59	0.60	0.61	0.70	0.69	0.63	0.55	0.57	0.60	0.60
Air leakage class Cfm/100 ft^2 @1 iwg†	121	370	96	36	34	341	58	70	441	606	394	490
Plenum or terminal box pressure (Pa) *	245	-260	79	79	480	29.5	47	47	50	18	-	16

† Air leakage class is based on the measured duct ELA at 25 Pa and the calculated leakage flow at 250 Pa static pressure, using the measured flow exponent.
* Average value of pressure pan measurements on all registers.

SUPPLY DUCT ELAS AT 25 Pa (ELA_{25}). The normalized leakage area (ELA_{25}) of supply ducts varied widely from system to system, ranging from 0.1 to 7.7 cm^2 per square meter of floor area served, and from 0.7 to 12.9 cm^2 per m^2 of duct surface area. In one VAV system, the ELA_{25} normalized by the duct surface area of the section upstream of the VAV boxes was found to be eight times smaller than that of the downstream branches. Normalized ELAs of the four sections downstream of mixing boxes in system L5 were much larger than those of the other systems tested: their ELAs ranged from 2.0 to 7.7 cm^2 per m^2 of floor area served, and from 7.8 to 12.9 cm^2 per m^2 of duct surface area.

AIR LEAKAGE CLASS. Overall, air leakage classes for the main supply ducts (upstream of VAV or mixing boxes) for all systems tested ranged from 34 to 246, while those downstream (usually branches) varied widely from 58 to 606. Compared to other duct sections studied by Fisk et al. 1999, our new data showed a much wider range of air leakage classes for sections downstream of VAV boxes, or mixing boxes if any. The leakage classes of all duct sections (including return ducts) ranged from 34 to 757. The median based on the sample presented is about 300.

OPERATING PRESSURE. Operating pressures varies significantly among different systems, and among different sections of the same systems. Duct sections or branches downstream of terminal boxes had average operating pressures similar to the operating pressures observed in the small-building systems.

AIR LEAKAGE RATIO. Table 2 provides rough estimated air leakage ratios for Systems L1 and L2. In system L1, there was a significant pressure drop between the supply plenum and the register outlets. Taking half of the value measured in the supply plenum is a way to estimate the operation pressure in light commercial buildings. Since the static pressures before the exits of registers vary along the duct system, taking the average of these pressures is another estimate of the average operating pressure in the supply duct. We used digital pressure gauge with a tube going through a sealed register-size pan, which was designed to fully cover a register during normal system operation to obtain static pressure at the register. The estimate of the supply section's air leakage fraction is 21% based on the first method (half plenum pressure), and 10% if using the average pan pressure as the input for operating pressure. The estimated air leakage fraction for the return section is 23% based on the method of half plenum pressure, and 6% if based on the average pan pressure method. As discussed in the approach section, Walker et al. (1998) have used essentially the same method to estimate air leakage from residential ducts, and they estimated that the maximum uncertainty was 40% of the measured air-leakage rate. By using the flow-subtraction method, the estimation of the leakage fraction for supply section in system L1 is 3%, which is associated with the combined uncertainty of ±16%. A comparison between the two methods indicates that the leakage fraction for the supply duct of system L1 would be in the range from zero to 19%. For system L2, the estimated air leakage fraction for the supply section is 26% based on the method of half plenum pressure, and based on the average pan pressure method. By using the flow-subtraction method, we measured a leakage fraction of 17% associated with the uncertainty of ±16%. With the uncertainties pertaining to the estimation, these results were in agreement, ranging approximately from zero to 33%.

Table 2. Estimates of air leakage ratios in two large commercial building systems.

Method	Leakage ratios based on the two methods (ELA/operating pressure; flow difference between up/downstream)		
	ELA and half plenum pressure	**ELA and average pan pressure**	**Fan flow – Sum of register flows**
System L1 (supply)	21%	10%	3%
System L1 (return)	23%	6%	-
System L2	26%	26%	17%

Overall, given the uncertainties associated with the two different methods used in this study, the range of the estimated leakage fractions in System L1 and L2 is similar to the findings in a previous study (Fisk et al. 1999). In that study, the estimated air-leakage ratios as the percentage of the inlet airflow rates varied widely from zero to approximately 30% with most of the estimates falling between 10 and 20%.

4.2 Conduction losses through ducts.

We calculate the temperature difference between supply plenum and terminal units (registers, VAV boxes) at the end of each temperature swing as a way to assess magnitudes of thermal loss through conduction in different systems. Table 3 presents average temperature rise (+, in cooling mode) or drop (-, in heating mode) relative to the supply plenum for each of theregisters. The overall average values in the right column can be used as indications of the heat conduction impacts through ductwork.

Table 3. Temperature rise/drop and effectiveness in registers or terminal boxes.

System type		Operating Mode	Temperature rise/drop at end of heat/cooling-ON swings (°C) (Cumulative temperature effectiveness)				
			Supply register A	Supply register B	Supply register C	Supply register D	Average
Large systems	L1 CAV store	Heating	-1.5 *(0.96)*	-2.5 *(0.95)*	-	-	-2.0 *(0.96)*
	L2 CAV office	Heating	-0.3 *(0.98)*	-4.2 *(0.84)*	-6.2 *(0.77)*	-	-3.6 *(0.87)*
	L3 VAV office	Cooling	4.4 *(0.73*)*	1.8 *(0.90*)*	-	6.5 *(0.62*)*	4.3 *(0.75*)*
			11.8 *(-)*	4.5 *(0.76*)*	11.0 *(-)*	-	9.1 *(-)*

Notes:

- Data in Italics indicate the cumulative temperature effectiveness for CAV systems during normal operating hours, or for the VAV system during one peak-hour (numbers marked with "*" in parenthesis). The effectiveness is an estimate of energy delivery effectiveness for the respective terminal units.
- Data in the shaded cells are for VAV boxes, not registers.

For two large CAV systems (L1 and L2) tested in heating mode, the average temperature drop (at the end of each temperature swing) between the supply plenum and the supply registers ranged from 2 to 3.6 °C, while the temperature drop in individual registers ranged from 0.3 to 6.2 °C. The corresponding cumulative effectiveness of downstream registers was 0.77 and 0.98. Within each of the systems, the further the distance downstream of the supply plenum, the lower the cumulative effectiveness.

For the VAV system (L3) tested in cooling operation, the supply temperatures swung periodically, as did the air temperatures exiting the supply registers. The temperature difference between supply-registers and supply-plenum thus varied accordingly. The temperature difference between the supply plenum and the terminal units (registers, VAV boxes) at the end of each temperature swing was used to indicate magnitudes of thermal loss through conduction of different systems. On average, the temperature rises (at the end of each temperature swing) between the supply plenum and VAV boxes ranged from 1.8 to 6.5 °C, while average temperature rises between the supply plenum and the supply registers ranged from 4.5 °C (without induction unit) to almost 12 °C (with induction unit). Our monitoring results of velocity pressure in the main trunk and branches suggested that during some short periods of time, the total fan flow was fairly constant. For example, between 1 PM and 2 PM, the dynamic pressure ranged from 70 to 77 Pa with an average of 74 Pa. The corresponding fan flow ranged within ±3% of its average, indicating little change in the fan flow between 1 PM and 2 PM. Since the dynamic pressure in VAV box B was quite stable during the same hour, the short-term aggregated temperature effectiveness can be used to estimate the thermal conduction loss for the VAV branch. Additional temperature rises in registers downstream of a VAV box rendered the temperature effectiveness of downstream registers significantly lower than that of their parent-VAV box during the peak-hour. For example, the temperature effectiveness of register B was 0.76, about additional 14-percent points' reduction for the temperature effectiveness in VAV box B (0.90). Assuming register B was representative of the registers in this particular VAV branch, the actual thermal losses (heat gains) through duct conduction downstream of VAV box B account for additional 14-percent points of the heat gain in the branch during the peak-hour period.

Overall, The effectiveness $((T_{register} - T_{room})/(T_{plenum} - T_{room}))$ was between 0.77 and 0.98 for the two CAV systems tested in heating mode, with average temperature drops of up to 4 °C. As expected, the effectiveness decreased with the distance downstream of the supply plenum. For the one VAV system in a large building that we tested in cooling mode, the temperature rise ranged between 2 °C and 12 °C. In this VAV system, about a quarter of the total cooling energy was lost before it was delivered to each of the VAV boxes during one particular peak-hour (1 PM to 2 PM). During that same period, about 14% of the potential cooling energy delivered to a particular register was lost downstream of its parent VAV-box.

5 Conclusions and recommendations

It is clear that there can be significant air leakage through duct systems in large commercial buildings, similar to what has been found in residences and light commercial buildings. Although we cannot draw any conclusions about the population of buildings in California based upon the few buildings that we have tested, it is clear that there can be significant leakage, and that there are large variations in leakage levels between and within building systems. Based upon estimates of air leakage ratios in two CAV systems tested, the system energy losses induced by air leakage can be significant (up to approximately one-third). It is worth continuing our pursuit of energy savings by means of duct sealing in large commercial buildings.

The supply air temperature changes associated with conduction losses were clearly shown to be well above the "designer's rule of thumb" of 0.55°C (1 °F), ranging between 0.3 °C and 6.2 °C (0.5 to 11.2 °F). As thermal losses have been shown to have energy impacts similar to, if not equal, those for leakage, it is clear that the energy savings potential associated with these losses is also significant. Moreover, it is also clear that the energy savings associated with the use of VAV systems are being systematically reduced by conduction losses. Specifically, as the flow and velocity through the ductwork is reduced by the VAV dampers, the conduction losses increase, which forces the VAV dampers to open further to increase the flows to meet the loads, thus offsetting potential savings intended from the VAV systems.

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